

SELECTIVE ESCAPE OF GASES *

by

E. J. ^{III}Opik

Armagh Observatory, Northern Ireland
and
Department of Physics and Astronomy
University of Maryland, U.S.A.

Technical Report No. 276

* This research was supported by the National Aeronautics and Space Administration
Grant NsG 58-60.

SELECTIVE ESCAPE OF GASES*

E. J. Öpik

Armagh Observatory, Northern Ireland

and

Department of Physics and Astronomy, University of Maryland, U.S.A.

Summary

16719 over

Formulae for gas-kinetic escape of neutral and ionized gas from celestial bodies are set up, free from usual simplifications and applicable to the highest rates. It is shown that the isothermal model with a constant escape lifetime becomes physically meaningless when the atmospheric mass exceeds a certain, quite modest, limit and the exospheric base disappears; this defines an overall upper limit to the rate of gas-kinetic escape from a body of given mass; the limit is rather low, by cosmic standards. Absolute upper limits to selective escape are calculated. A solar nebula could not have lost by escape more than 10^{-13} - 10^{-17} of Jupiter's mass in hydrogen, nor could Jupiter's protoplanet have lost very much more. Escape to space cannot account for the deficiency of hydrogen in the atmospheres of the outer planets; other possible processes are considered; snowing-out of hydrogen in a rotating flattened solar nebula may account for the separation of hydrogen from helium. For the Earth, the upper limit of loss of hydrogen equals one-third of the water equivalent of the oceans, but the actual loss as determined by the oxidation of the crust, may equal only 14 per cent of the oceans.

The escape from Earth of an equivalent amount of hydrogen would require conditions, very different from those prevailing now; a suggestion is made to this effect, regarding possible intense volcanic and plutonic activity on Earth

* This research was supported by the National Aeronautics and Space Administration Grant NsG 58-60.

during the first undated 1.5×10^9 years of the Earth's history. For Venus, a probable exospheric temperature of about 7000°K is estimated; without a cold trap, hydrogen may have escaped freely. However, for a crust similar to the terrestrial, the amount of oxygen bound in oxidation can hardly be more than corresponding to 400-800 metres of water; the disappearance of water from Venus would thus indicate a several times smaller initial store than on Earth. Residual oxygen in the atmosphere could have disappeared through ionic escape. At 7000°K the escape of O^+ during 4.5×10^9 years could account for the disappearance of ten times the terrestrial amount of free O_2 even when inhibited by a magnetic field.

1. Introduction

Evidence has been accumulating for an excess of helium over hydrogen in the atmospheres of the outer planets. The number ratio of He to H_2 appears to be of the order of 40 in Jupiter (Öpik 1962 b), and 3 at least in Uranus and Neptune (Herzberg 1952). The interior of Jupiter being in all probability composed mainly of solid hydrogen (Ramsey 1951, DeMarcus 1958, Wildt 1961), there arises a cosmogonic puzzle as to how the excess of helium in its atmosphere may have come about (Urey 1959), in view of the excess of hydrogen in cosmic mixtures which outnumbers helium in a ratio of about 7 to 1 (Aller 1953). An alternative of nitrogen, instead of helium, providing the matrix of the atmospheres of the giant planets is unacceptable as, in the presence of free hydrogen, it either would have been all reduced to ammonia, or would have removed all the hydrogen (Öpik 1962 b). Besides, an excess of nitrogen over hydrogen would even be more difficult to understand than an excess of helium.

There are, of course, so-called helium stars in whose atmospheres helium is overabundant as compared to hydrogen; these may represent remnants of

exhausted stellar cores in which the hydrogen has burned to helium and whose envelopes have blown off in a thermonuclear explosion. The sun is not such a remnant, and an explosion would have carried away the entire hydrogen-containing envelope with all the other elements including helium; the helium abundance in the outskirts of a solar nebula cannot have come about through such a cataclysm. Causes other than thermonuclear explosions must have worked in producing the peculiar composition of the atmospheres of the giant planets; possibly, some of the helium stars may also have been influenced by similar causes, without the intervention of nuclear reactions.

It may appear that the preferential escape to space of hydrogen, as a lighter gas, could provide an explanation. It is shown below that, quantitatively, the explanation does not hold even in the case of the most favorable assumptions. Gas-kinetic escape, as a particular case of diffusion, is subject to severe limitations owing to the finite collisional cross-section of the molecules, and cannot serve to remove in reasonable time masses of planetary order. Only superficial changes, affecting the small atmospheric masses of the terrestrial planets, could have been achieved in such a manner. The separation of hydrogen and helium in the outer planets must be attributed to some other process - most likely to snowing-out of solid hydrogen in the solar nebula, whose flattened disc may have been kept at a temperature of some 4 °K when dust was shielding solar radiation and starlight alone was available (Opik 1962b).

In the following some aspects of gas-kinetic escape, especially its quantitative limitations, will be examined. In particular, it is shown that oversimplifications of the isothermal model which often are introduced may grossly exaggerate the possibilities of escape.

2. The Isothermal Model

Jeans (1925) proposed a model used also by Spitzer (1952), namely that of an isothermal atmosphere in diffusive equilibrium; it yields high rates of absolute and selective escape, and is well suited for obtaining upper-limit values. Spitzer (1952) introduced certain simplifications, amounting to a calculation of escape lifetime irrespective of the actual position of the escape layer, valid however only for low rates of escape; for marginal upper-limit estimates the simplifications cannot be used. In this respect credit must be given to Urey (1959) who realistically applied Jeans' formula to the actual escape layer, however without allowing for its increased radius.

The equivalent of Jeans' precise escape formula for a spherical surface of radius r (cm) can be written (Opik and Singer 1961) as

$$F_r = 4\pi r^2 N X u (1 + B) e^{-B} \quad (1)$$

molecules of species X escaping per second through the surface, with

$$u = (kT/2\pi m)^{1/2} = 3637(T/\mu)^{1/2} \text{ (cm/sec)}. \quad (2)$$

Here N is the total number density cm^{-3} ; X is the relative abundance, m the mass, μ the relative molecular weight ($O = 16$) of the particular molecular species, k Boltzmann's constant, T the temperature $^{\circ}\text{K}$. B , the escape parameter, is given by

$$B = GMm/(rkT) = ms^2/(2kT) = 6.013 \times 10^{-9} \mu s^2/T \quad (3)$$

or

$$B = 8.023 \times 10^{-16} M\mu/(rT); \quad (3a)$$

it represents the ratio of gravitational potential energy to the thermal

energy kT per molecule. G = gravitational constant, M = mass inside spherical surface r , s = escape velocity from r to infinity, the mass outside r being assumed to be negligible as compared to M , as would correspond to a superficial "atmospheric" layer. Equation (1) refers literally to a certain "escape level" from which molecules can move out to space unhindered. For a major light constituent usually $X = 1$, on account of diffusion.

The mass escaping per unit time is

$$dM/dt = -mF_r = -1.66 \times 10^{-24} \mu F_r. \quad (4)$$

The actual escape effectively takes place from an "exospheric base" whose overlying mass load corresponds to the gas-kinetic free length of path, conveniently defined by

$$\sigma \Sigma N = \frac{1}{2} \quad (5)$$

(Öpik and Singer 1961), where

$$\Sigma N = \sum_r N = \int_r^\infty N dr. \quad (6)$$

For not-too-small values of B

$$\sum_r N = \bar{H} N_r \quad (7)$$

can be assumed, with \bar{H} , the mean scale height, being defined through

$$\bar{H} = kT/mg = r/B, \quad (8)$$

g being the acceleration of gravity at r. For order-of-magnitude calculations, equations (7) and (8) can be used down to $B \geq 1$. For $B < 1$, $H = r$ can be conveniently substituted. The escape of minor constituents from the base of the exosphere must be supplied by ~~diffusion~~^{diffusion} from underneath. At small values of B and high rates of escape, the supply may become inadequate, upsetting the postulated diffusive equilibrium and reducing NX at the exospheric base, as well as the rate of escape as compared with that for diffusive equilibrium. By neglecting this "bottleneck of diffusion" the escape is overestimated; this would suit our present purpose of obtaining upper limits.

In the present case, however, we are concerned with the depletion of major constituents (hydrogen), which may concentrate to 100 per cent near the top while sufficiently abundant underneath. The bottleneck of diffusion is irrelevant in such a case and equation (1) defines the escape flux without exaggeration. In what follows next, for the escaping major constituent we may set $X = 1$, $NX = N$, $\bar{H} = H$, $\bar{B} = B$, $\bar{m} = m$ in equations (1) and (5) - (8).

In diffusive equilibrium the Boltzmann thermodynamic formula holds,

$$N_1/N_2 = e^{B_1 - B_2}, \quad (9)$$

or

$$N = N_0 e^B, \quad (9a)$$

where N_0 is the equilibrium density "in infinity", a somewhat vague effective quantity. In a real case, N_0 must be small.

Substituting (9a) into equation (1), the exponential factors cancel out. With B usually of the order of 10 or more, according to equation (8) the scale height is small as compared to the radius, the atmosphere is comprised within a relatively narrow sheet, r varies little, and F_r is approximately constant whatever level and number density is assumed in equation (1). The

equation, applied to an arbitrary level for which the isothermal and diffusive equilibrium assumptions hold, would yield the correct value of the escape flux, although the level may not be the exospheric base but may be placed somewhere deep underneath. Spitzer (1952) also neglected the unity term, small as compared to B in the brackets of equation (1) and arrived thus at an elegant formula for the lifetime of a gas escaping from above a certain level, independent of its number density, N , at this bottom level. Spitzer's formula has been widely used without realizing its actual limitations.

Thus, it may seem that, by applying Spitzer's formula or its more precise equivalent, equation (1), to an arbitrary isothermal level at s , T , and B constant, the escape flux may be made arbitrarily large by simply increasing the gas density, N , at this level. This may be formally correct, but would, in some instances, require structures which cannot exist in the real universe.

When $N = N_1$ is increased at a given level, according to equation (9) the density increases in the same proportion at all other levels; as a result, the exospheric base is shifted outwards, r increases and B at the base decreases. When $B < 1$, $H \sim r$, equation (5) reduces to $\sigma r N = \frac{1}{2}$; yet, when $r \rightarrow \infty$, $N \rightarrow N_0 = \text{const.}$ according to equation (9a), and $\sigma r N \rightarrow \infty$, not $\frac{1}{2}$. Condition (5) can be fulfilled only up to a certain maximum value of N_1 , above which no exospheric base can exist, the atmosphere merges into the medium and escape is replaced by diffusion. Spitzer's formula for the escape lifetime can be valid only to a certain upper limit of the gas density, N , or the escape flux, F_e . On the other hand, when escape is increased by decreasing B , at $B < 1.5$ the atmosphere blows off and gas-kinetic escape cannot take place [see below, condition (13)].

An isothermal gas sphere has, theoretically, infinite mass and cannot, therefore, stretch out isothermally to infinity; however, an isothermal structure, as a working approximation, is acceptable when its density somewhere merges into the interstellar or interplanetary background.

The limitation of escape flux becomes obvious when equation (9a) is substituted into (1) ($X = 1$),

$$F_r = 4\pi r^2 N_o u(1 + B); \quad (10)$$

with a reasonable upper limit to N_o , the escape loss is limited and cannot be arbitrarily increased. We may set, as a condition of the static existence,

$$N_o \ll N_s, \quad (11)$$

where N_s is the interstellar (for a solar nebula) or interplanetary gas density (for planets or protoplanets). At this condition, N as defined by equation (9a) may become equal to N_s at a certain finite value of $B > 0$, or a finite distance, rendering possible a smooth fit of atmosphere to medium.

On the other hand, the mere existence of an exospheric base and of the process of gas-kinetic escape requires

$$N \gg N_s \quad (11a)$$

at the base. Without this condition, the boundary of the gas sphere loses its identity; it would merge into the surrounding medium, diffusion and hydrodynamic flow becoming the means of exchange of matter, instead of escape.

3. Selective Escape.

When condition (11) is violated, the postulated isothermal gas structure in hydrostatic equilibrium cannot exist. The interstellar or interplanetary gas density being lower than required by isothermal equilibrium with the gas sphere, there will be an excess of pressure and the gas from the top of the sphere will rush into the surrounding vacuum. Two extreme cases may be distinguished schematically when

$$N_0 > N_s . \quad (12)$$

(a) Isothermal expansion. When the supply of energy is sufficient to keep the streaming and expanding gas at an isothermal level, it will stream out into the surrounding space; the time scale of diffusive separation of the gaseous constituents being large as compared to that of hydrodynamic flow, no separation takes place and the material is lost to space non-selectively, by streaming and not by gas-kinetic escape.

(b) Adiabatic expansion. When the supply of energy is negligible, isothermacy cannot be maintained and an essentially adiabatic state sets in. Equation (9) is no longer valid. Unless the thermal energy is too high, the sphere maintains finite dimensions. Diffusion is superseded by mixing, and the composition of the gas is uniform throughout the atmospheric layer. Differential or selective escape takes place, the loss of each component being given by equations (1) - (3) when r is the radius of the exospheric level, T its actual temperature, and N_X the exospheric density of the particular component. Contrary to the isothermal model, no substitution by other levels is admissible. Equations (5) - (8) remain valid when $\sum N$ and N_r refer to the sum of all components, and $\sigma = \bar{\sigma}$, $m = \bar{m}$, $\mu = \bar{\mu}$,

$B = \bar{B}$ [calculated from equation (3) with $\mu = \bar{\mu}$] are average values for the gas mixture.

The thermal energy of gas-kinetic translational motion equals $1.5 kT$ per molecule; if this exceeds the gravitational energy, or when, according to equation (3), for the gas mixture

$$\bar{B} < 1.5,$$

the top of the atmosphere blows off; the loss of gas may then be almost arbitrarily high but indiscriminate as to species. An overall condition for the possibility of selective escape, equally applicable to the adiabatic and the isothermal cases, is thus

$$\bar{B} > 1.5 \quad . \quad (13)$$

For the isothermal case, this may be superseded by condition (11) which, in conjunction with equation (9a), yields the condition for selective escape as

$$\bar{B} > \ln(N/N_s) \quad , \quad (14)$$

valid when

$$N/N_s > 4.5 \quad ;$$

otherwise condition (13) holds as the overriding one.

The rate of escape generally increases with decreasing B ; therefore, equations (13) and (14) also define the maximum possible rates of selective

escape. These rates are to be calculated from equation (1) as applied to the actual escape level, or the base of the exosphere, without substitution. When condition (11) is fulfilled, the isothermal case with diffusive equilibrium can be assumed as a basis; when not, the adiabatic model with uniform composition is to be preferred.

4. Rate of selective escape.

A combination of equations (5), (7), and (8) yields for the escape level or exospheric base a total number density

$$N = \bar{B}/(2\sigma r) \quad (15)$$

Equation (15), however, breaks down at small values of \bar{B} ; when $\bar{B} < 1$, an effective value of $\bar{B} = 1$ should be used. \bar{B} itself is a function of r ; when the distribution of density with altitude, $N = f(r)$, is known, the position of the escape level is found from (15) by trial and error. In practice, guesswork is inevitable. Eliminating T/μ in equation (2) with the aid of (3a), we have also

$$u = 1.030 \times 10^{-4} (M/rB)^{1/2} \quad (16)$$

Substituting equations (15) and (16) into (1), we obtain a general expression for the selective escape flux, when universal constants are numerically evaluated, as follows:

$$F_x = 6.474 \times 10^{-4} X(rM)^{1/2} \bar{B} B^{-1/2} (1 + B) e^{-B} / \bar{\sigma} \quad (17)$$

With $\bar{\sigma} = 1.8 \times 10^{-15} \text{ cm}^2$ as for typical gas-kinetic collisions of not too high energy (hydrogen at small multiple of room temperatures),

$$s^2 = 2GM/r \quad (18)$$

or

$$s = M(2G/Mr)^{1/2} = 3.653 \times 10^{-4} (M/r)^{1/2} \quad (19)$$

as the escape velocity for neutral molecules, and the total rate of mass loss through escape of the component x being

$$dM_x/dt = - 1.660 \times 10^{-24} \mu F_x \quad (20)$$

(g/sec), the relative rate of loss of mass, expressed in units of M , the total mass of the gaseous sphere, is reduced to

$$\frac{1}{M} \frac{dM_x}{dt} = - 2.18 \times 10^{-16} \mu X s^{-1} \bar{B} B^{-1/2} \cdot (1 + B) e^{-B} (\text{sec}^{-1}), \quad (21)$$

when in equation (17) Mr is substituted from (19) and F_x is inserted into (20). For $\bar{B} < 1$, $\bar{B} = 1$ should be used as the best approximation, whereas for B its actual value shall be taken even when small. The values of s , \bar{B} and B should correspond to the actual base of the exosphere. Except for dimensionless parameters, the fractional rate of mass loss is inversely proportional to s , the escape velocity (cm/sec) from the base of the exosphere. This remarkable formula is quite general, the only somewhat inaccurate parameter used being $\bar{\sigma}$, the collisional cross section of the gas molecules. The numerical factor in equation (21) is inversely proportional to $\bar{\sigma}$. On the other hand, in isothermal equilibrium the exospheric density $N \sim \sigma^{-1} \sim e^B$ for a given atmospheric mass distribution, so that the product $e^{-B} \sigma^{-1}$ is constant, and the actual rate of escape little depends on σ .

5. Ionic escape.

The formulae for ionic escape can be derived from the preceding formulae for escape of neutral gas, although in actual cases the definition of the escape parameters (N,B,T) is less unambiguous. On account of electrostatic fields caused by the diffusion of electrons, the weight of the ions is reduced - to one-half of full gravity when only one ionic species is present, and in different proportions when several species occur. The values of B are reduced in the same proportion as gravity is decreased, in comparison to those of equations (3) and (3a). When two ionic components are present whose number densities are yN_e and $(1-y)N_e$, N_e being the electron density, and whose relative molecular weights are μ_1 and μ_2 , respectively, their escape parameters are given by

$$B_1' = \frac{1}{2} B_1 \left[1 + (1-y)(1-\mu_2/\mu_1) \right] \quad (22)$$

and

$$B_2'' = \frac{1}{2} B_2 \left[1 + y(1-\mu_1/\mu_2) \right] \quad (23)$$

(Öpik 1962a), where B_1 , B_2 are the values for the neutrals; however, in the case of negative values of B_1' or B_2'' , zero must be assumed. The ionic average of B is

$$B_i = \frac{1}{2} B \quad (24)$$

The Coulomb collision cross section of ions strongly depends on velocity, so that a straight average value cannot be used, unlike neutral molecules. Also, the escaping ions belong to the high-velocity tail of the Maxwellian distribution and have thus smaller cross sections than the average thermal ions. Their

average kinetic energy at the escape base is approximately $(\frac{1}{2} \bar{B} + 1.5) kT$, corresponding to an effective temperature of

$$T_i = (1 + \frac{1}{3} \bar{B}) T \quad . \quad (25)$$

Hence their collisional cross section for Coulomb interactions (Öpik and Singer, 1961) can be set equal to

$$\sigma_c = 2.25 \times 10^{-16} \left[(1 + \frac{1}{3} \bar{B}) T \right]^{-2} \cdot \log_{10}(1 + 10^8 T^3 / N_e) (\text{cm}^2). \quad (26)$$

If z is the degree of ionization, or the ratio of electron density to total number density, the effective collisional cross section becomes

$$\bar{\sigma} = z \sigma_c + (1 - z) \sigma_n \quad , \quad (27)$$

with $\sigma_n = 1.8 \times 10^{-15} \text{ cm}^2$.

With respect to the effective scale height the actual situation for ions is rather complicated. Nevertheless, for the upper portion of the ionosphere equations (15) and (16) may be assumed to remain valid, with $\bar{B} = \bar{B}_i$ as an average of equations (22) and (23), usually close to expression (24), $X = y$ for the "first" component and $\bar{\sigma}$ defined through equation (27). Equation (21) as adapted to ionic escape in the absence of a magnetic field then transforms into

$$\frac{1}{M} \frac{dM_i}{dt} = - 2.18 \times 10^{-16} \mu_i y_i^{-1} \bar{B}_i B_i^{-1/2} \cdot (1 + B_i) e^{-B_i} (1 - z + z \sigma_c / \sigma_n)^{-1} (\text{sec}^{-1}), \quad (28)$$

valid for the actual ionic escape base; $z \sim 1$ is expected there to be valid,

whence \bar{B}_i as for ions alone is assumed. For the calculation of the ratio σ_c/σ_n , equation (26) can be used but with a different numerical factor, equal to 1.25×10^9 ; $B_i = B_1$ is defined by equation (22); this, and \bar{B}_i are as for ionized gas, while B and s remain as for neutral gas, all at the escape level of the ions, or at the base of the iono - exosphere.

It may be difficult to define the position of the ionic escape level; observational data for the Earth, relating to the distribution of electron density with altitude, are not directly applicable as they are governed by the geomagnetic field. Generally it can be assumed that the ionic escape base is placed well out in space, above the escape level for neutral gas. This qualitative feature, however, is insufficient. If isothermacy more or less holds between the two levels, as an approximation we may use the Jeans-Spitzer compensation of the N and e^{-B} factors in equation (1), $N e^{-B} = \text{const.}$, and apply the ionic escape formula to the base of the neutral exosphere, without regard to the value of σ , but with correcting factors for the non-compensated variables r^2 and $(1+B)$ which must refer to the actual ionic escape level. In the absence of a magnetic field, the ionic escape flux then follows from equation (21) as

$$\frac{1}{M} \frac{dM_i}{dt} = - 2.18 \times 10^{-16} \mu_i X_i s^{-1} \cdot \bar{B} B^{-1/2} [(r_i/r_0)^{2+B_i} (r_i/r_0)] e^{-B_i}, \quad (28a)$$

with X_i being the extrapolated abundance of the ion at the neutral escape level, calculated on the assumption of isothermal equilibrium [equation (9)] from a given density N_i at the ionic base; s is that for neutral gas, B for neutral gas of species i , B_i for the ionized species [usually $B_i = \frac{1}{2} B$ for the major constituent, see equation (22)], and \bar{B} is the average for neutral gas only, all the parameters referring to the neutral escape level; r_0 and r_i are the radii of the neutral and ionic escape levels. There is some minor uncertainty

in the ratio r_i/r_0 as depending on the actual position of the ionic escape base, but it is much less troublesome than the uncertainty in σ_c and e^{-B_i} which affects equation (28). The major uncertainty rests with X_i , the extrapolated effective ionic abundance; from terrestrial experience, $X_i \sim 0.1$ for electron density; in such a case by setting $X_i = 1$, equation (28a) is expected to lead to an overestimate of the escape rate by an order of magnitude; however, theoretically there is no limit to X_i which may even exceed unity.

Equations (28) and (28a) presume the absence of a magnetic field. In a magnetic dipole field ionic escape can take place only from near the magnetic poles, from where the lines of force reach far enough into space, to be lost in the interplanetary or interstellar field. For the earth this happens at about 13 earth radii, implying lines of force starting at geomagnetic latitude 74° or higher; the area of escape is then 0.04 of the total. By analogy, we may assume that in the presence of a magnetic field, the ionic escape rate is decreased roughly by a factor of 25, as compared with the values given by equations (28) and (28a).

6. Some Applications.

(a) Nebula of solar mass.

For a spherical nebula of solar mass the minimum heat flux can be assumed equal to that of the present solar output plus starlight, which would be correct at a stage when the sun had already formed by gravitational contraction (within about 10^7 years), leaving a residual nebula behind. The nebula, prevented from falling into the sun by its original or acquired angular momentum, would ultimately assume a flattened shape, the matrix for planet formation. For order-of-magnitude estimates of escape, a spherical model is still admissible; at an early stage, when s is small and the escape is greatest [cf. equation (21)], it will, indeed, be practically spherical. The surface temperatures are always so low that no significant ionization can occur (H I region), so that the

equations for neutral gas alone will be used.

The radiative equilibrium temperature at the exospheric base can be calculated on the black body model; the presence of dust ensures the possibility of this procedure. With 5800°K as the present photospheric temperature, and a radius of $1/215$ a.u. of the sun, and 3.66°K as the black body equilibrium temperature for starlight plus cosmic rays (7×10^{-3} erg/cm² sec from starlight, 3×10^{-3} from cosmic rays), the equilibrium temperature at a radius of A a.u. is

$$T = (2.4 \times 10^{10} A^{-2} + 180)^{1/4} (^{\circ}\text{K}). \quad (29)$$

The escape velocity equals

$$s = 4.22 \times 10^6 A^{-1/2} \text{ (cm/sec)}, \quad (30)$$

and, from equation (3),

$$B = 1.075 \times 10^5 \mu (AT)^{-1}. \quad (31)$$

With

$$r = 1.5 \times 10^{13} A \text{ (cm)}, \quad (32)$$

$\bar{\sigma} = 1.8 \times 10^{-15} \text{ cm}^2$ and equation (15),

$$N = 1.99 \times 10^6 \mu (A^2 T)^{-1} \text{ (total)}, \quad (33)$$

when

$$N_x = XN, \quad (34)$$

and subject to the limitation (11a). According to this, the number density at the exospheric base must exceed that of the interstellar medium ,

$$N \gg N_s \sim 1 \text{ cm}^{-3} \quad . \quad (35)$$

With $X = 1$ as an upper limit, $\bar{B} = B$, or for escape of only one pure component - molecular hydrogen, $\mu = 2$ - Table 1 has been calculated, according to equations (29) - (33) and (21). Condition (11) is always fulfilled, so that the

TABLE 1

Escape of molecular hydrogen from a nebula of solar mass (M) and luminosity

| A | T | S | $\bar{B} = B$ | $N = N_X$ | $-\frac{1}{M} \frac{dM}{dt}$ | $\frac{\Delta M}{M}$ in | $\frac{\Delta M}{M}$ in |
|------|-------|-----------------------|---------------|------------------|------------------------------|-------------------------|---------------------------------|
| a.u. | deg K | 10^5 cm/sec | | cm^{-3} | sec^{-1} | 10^8 years | $4.5 \times 10^9 \text{ years}$ |
| 10 | 124 | 13.3 | 174 | 321 | 10^{-84} | 4×10^{-79} | 2×10^{-77} |
| 100 | 39.4 | 4.22 | 54.5 | 10.2 | 8×10^{-43} | 2×10^{-27} | 1×10^{-25} |
| 400 | 19.7 | 2.11 | 27.3 | 1.28 | 5×10^{-31} | 1.4×10^{-15} | 7×10^{-14} |
| 1000 | 12.4 | 1.33 | 17.4 | 0.32 | 7×10^{-27} | 2×10^{-11} | 1×10^{-9} |

isothermal model is consistent. As to condition (35), it is violated in the last two lines of the table, for $A = 400$ and 1000 ; for these, the nebula loses its exospheric identity and the concept of gas-kinetic escape does not hold; exchange with the surrounding medium proceeds by way of diffusion, a very inefficient process, too (Öpik 1962b); and, instead of loss, there will be gain by accretion.

The last two columns of the table give the total relative loss by escape, $\Delta M/M$, over periods of time which are allegedly much longer than the time of

existence of the nebula. These losses are negligible even compared to the mass of the gaseous outer envelope of Jupiter which is of the order of 10^{-6} solar mass (De Marcus 1958, Öpik 1962b). At $A = 200$ which is an upper limit for the exospheric model, $\Delta M/M \sim 10^{-20}$ or about 10^{-14} of Jupiter's atmosphere. Clearly, no significant separation of the gaseous constituents in the outer portions of the solar nebula could have taken place according to this model.

With other sources of heating supporting a higher temperature, the escape may be increased. With $B = \bar{B} = 1.5$ according to condition (13) as the extreme lower limit for differential escape without the top "blowing off",

$$T = 1.43 \times 10^5 A^{-1}, \quad (36)$$

$$N = N_x = 28 A^{-1}, \quad (37)$$

and from equation (21) with $X = 1$, $\mu = 2$, $B = 1.5$,

$$\frac{1}{M} \frac{dM}{dt} = - \frac{2.98 \times 10^{-16}}{s}, \quad (38)$$

Table 2 has been calculated. L is the luminosity of the model,

$$L = (T/T_1)^4, \quad (39)$$

TABLE 2

Extreme upper limit of selective loss of molecular hydrogen from a nebula of solar mass, at $B = \bar{B} = 1.5$

| A | T | s | $N=N_x$ | N_0 | $\frac{1}{M} \frac{dM}{dt}$ | L | t | $\frac{\Delta M}{M}$ |
|------|-------|---------------|------------------|------------------|-----------------------------|-------------------|-----------------|-----------------------|
| a.u. | deg K | 10^5 cm/sec | cm^{-3} | cm^{-3} | 10^{-22}sec^{-1} | solar units | upper limit sec | upper limit |
| 10 | 14300 | 13.3 | 2.8 | 0.62 | 2.24 | 1.8×10^8 | 6×10^7 | 1.3×10^{-14} |
| 25 | 5720 | 8.44 | 1.12 | 0.25 | 3.53 | 1.1×10^7 | 9×10^8 | 3×10^{-13} |
| 100 | 1430 | 4.22 | 0.28 | 0.062 | 7.05 | 1.8×10^6 | 6×10^9 | 4×10^{-12} |

where T_1 is the temperature corresponding to solar luminosity and defined through equation (29). Without defining the extraordinary source of heating (one suggestion may be a nearby hot star, or a supernova explosion), the total energy expended must be somehow limited; arbitrarily, we assume an upper limit equal to the sun's radiation during 3×10^8 years or 10^{16} sec, whence a reasonable upper limit to the duration of excessive heating (quite artificially assumed to have somehow stayed at the limit of $B = 1.5$, not overstepping it) is set by

$$t \leq 10^{16}/L \quad (\text{sec}) \quad . \quad (40)$$

In such a manner, overall upper limits to the selective loss of hydrogen are found as given in the last column of Table 2. These are higher than those of Table 1, but are still negligibly small.

Thus, selective escape at any stage of evolution of the solar nebula is utterly inadequate to account for the scarcity of hydrogen in the outer envelopes of the planets. It might seem that sputtering by the impact of interstellar gas, or "interstellar wind" could contribute to the loss of hydrogen from the outskirts of the solar nebula. However, the impinging interstellar atoms and molecules will kick most of the nebular molecules inwards, and will themselves be trapped in the deeper layers to which they penetrate, on account of their high velocity (about 20 km/sec as the present translational velocity of the sun relative to interstellar gas).

It can be estimated that, for each ten impinging interstellar atoms there may be only one ejected hydrogen molecule (only one in the exosphere with sufficient velocity to escape, but mostly directed inwards or at a small angle to the horizon and trapped by subsequent collisions). There will be accretion, instead of loss.

If the incoming interstellar gas belonged to an H II region, with its hydrogen ionized but helium not, a magnetic field of the order of 10^{-3} gauss could have turned the hydrogen back, letting neutral helium through. At $A = 100$ a.u. (Table 1) and 0.1 cm^{-3} as the helium density, with 20 km/sec as the velocity of the stream, the preferential influx of helium captured by the cross section of the nebula would have amounted to 6×10^{12} g/sec or 8×10^{-6} solar mass in 10^8 years. This is of the order of Jupiter's outer envelope. However, it is improbable that the residual solar nebula, after the giant planets had formed (their interiors are not deficient in hydrogen) could have remained at $A = 100$ for 10^8 years. Most likely, the planets were already in their present positions, at about $A = 10$ a.u., and the sweeping time for removing the remnants of the nebula from between the planets was of the order of less than 3×10^5 years (Öpik 1962b); this would make the possibly accreted helium mass smaller by a factor of 10^5 , or about 10^{-10} solar mass, which is again negligible.

The most probable process which led to the formation of the helium-rich atmospheres of the giant planets on top of their solid hydrogen main bodies appears to consist in snowing-out of hydrogen from an extremely cold (4°K) flattened nebular disc; hydrogen snow may have then led to the formation of the main bodies which later collected the helium gas left behind (Öpik, 1962b).

Our estimates of the rate of selective escape have been based on a spherically symmetrical model of the nebula. A more complicated discussion of selective escape from a rotating flattened nebular disc leads numerically to the same conclusion, that is, of the inadequacy of escape (Öpik 1962b). The conclusion is quite general; it mainly depends on the gas-kinetic and thermodynamic properties of the gases, and very little is influenced by the macroscopic details of the gaseous models of astronomical dimensions to which the theory is applied.

(b) Jupiter - an overall upper limit to selective escape.

According to equation (21), for an overall upper limit of escape s and B must be given their lowest possible values. From equation (3) it also follows that

$$s \sim B^{1/2} T^{1/2} ,$$

whence, from equation (21), when $X = 1$ and $B = \bar{B}$,

$$-\frac{1}{M} \frac{dM}{dt} \sim \mu T^{-1/2} (1 + B) e^{-B} , \quad (41)$$

paradoxically, at given B the lowest exospheric temperature yields the highest rate of escape. According to equation (3a), for a constant mass this requires a maximum possible exospheric radius,

$$r \sim (BT)^{-1} . \quad (42)$$

With the present planets (except Mars and Mercury), there is little freedom in the choice of r which cannot much exceed the radius of the planet. Only in a hypothetical gaseous protoplanetary stage (which may not have taken place at all), a large value of r , with simultaneously low values of B , T , and s can be postulated.

Assuming as minimum value $T = 100^{\circ}\text{K}$ at the surface of the protoplanet, and $s = 1.1 \times 10^5$ cm/sec as a minimum for this temperature, for $\mu = 2$, $B = 1.5$ according to equation (3), equation (38) yields

$$-\frac{1}{M} \frac{dM}{dt} < 3 \times 10^{-21} \text{ sec}^{-1} \quad (43)$$

This, artificially conceived protoplanetary stage could not have lasted very long, certainly much less than 10^8 years or 3×10^{15} sec. Hence, through escape from the imaginary inflated gasball, the selective loss of hydrogen could not have exceeded 10^{-5} of the mass of the planet or, in the case of Jupiter, 1 per cent of its atmosphere.

The radius of the Jupiter protoplanet, corresponding to $s = 1.1$ km/sec, would have been about 3000 Jupiter radii or 1.4 astronomical units, far out of Jupiter's present satellite system. Both the size, and the lifetime of this fantastic gasball cannot have been as large as supposed. It is safe to state that Jupiter never could have lost more than one-millionth of its mass through selective escape of hydrogen.

During the present planetary stage, with $\mu = 1$, $T < 10^4$ °K, $s > 5 \times 10^6$ cm/sec, $B > 15$ as for atomic hydrogen in Jupiter's exosphere, equation (21) yields

$$-\frac{1}{M} \frac{dM_H}{dt} < 8 \times 10^{-28} \text{ sec}^{-1} ,$$

or, for $t = 1.4 \times 10^{17}$ sec as the age of the solar system, $\Delta M/M < 10^{-10}$.

This is very small as compared with the upper limit for the protoplanetary stage. For completely ionized hydrogen, $\gamma = 1$, $z = 1$, $B_i = \frac{1}{2} \bar{B} = 7.5$ at $T = 10^4$, $N_e \sim 10^8 \text{ cm}^{-3}$, $\sigma_c = 10^{-14} \text{ cm}^2$ according to equation (26), $\sigma_c/\sigma_n = 5$, equation (28) yields an upper limit to ionic escape of hydrogen from Jupiter equal to 180 times the limit for neutral hydrogen, or

$$\left| \frac{1}{M} \frac{dM_i}{dt} \right| < 1.4 \times 10^{-25} \text{ sec}^{-1} .$$

In 1.4×10^{17} seconds this gives

$$\Delta M_i/M < 2 \times 10^{-8} ,$$

thus still negligible, especially when it is considered that Jupiter's magnetic field would cut it down to a figure of about 8×10^{-10} , the same order as for neutral escape.

Considering that the temperature of Jupiter's exosphere is undoubtedly very much lower than 10^4 °K, the estimates are grossly exaggerated, the present rate of escape from Jupiter being practically nil.

(c) The Earth.

It is generally believed, and for good reason, that the terrestrial planets have lost all their original free gas which they acquired in the process of accretion; it has blown off, indiscriminately as to species, by being too hot ($\bar{B} < 1.5$) or too dense ($N_0 \gg N_g$), or both.

What atmosphere these planets own now has been apparently released from the interior, where it had been occluded in the solid crust or fluid magma.

We are here only interested in the material balance of the major atmospheric constituents. Of these, on Earth only hydrogen has been, and still is escaping, the other constituents (O, N) being bound firmly (large B value).

The hydrogen is supplied by photo-decomposition of water vapour,



In reaction (b), the molecular hydrogen is hard to break up, as it requires at least 14.7 eV in the strong absorption region; however, it will not accumulate indefinitely, but will recombine to water giving reaction (a) a second chance. This latter takes place at lower energies, intensely in the ultraviolet region shorter than 1850 \AA where enough photons are available to match any reasonable escape rates. The escaping hydrogen will thus always be available in atomic and not in molecular form.

After the first cataclysmic accretion and original loss of the proto-atmosphere, it can be assumed that present-day exospheric conditions more or less prevailed.

With $r = 7 \times 10^8$ cm, $s = 1.05 \times 10^6$ cm/sec as for the escape level, $\mu = 1$ as for atomic hydrogen, $X = 1$ as for a major light constituent (valid even now, when H has become a minor constituent of the atmosphere), equation (21) yields rates of escape as in Table 3, with the other data furnished by equations (3), (15) ($\bar{\sigma} = 1.8 \times 10^{-15}$) and (9a).

TABLE 3

Maximum rates of escape of neutral atomic hydrogen from Earth

| T $^{\circ}\text{K}$ | $\bar{B} = B$ | $N = N_s$ cm^{-3} | N_0 cm^{-3} | $-\frac{1}{M} \frac{dM_H}{dt}$ sec^{-1} | $\Delta M/M$ in 4.5×10^9 years |
|---------------------------|---------------|-------------------------------|---------------------------|---|--|
| 1500 | 4.45 | 1.78×10^8 | 2.4×10^4 | 2.8×10^{-23} | 4.0×10^{-6} |
| 2000 | 3.34 | 1.34×10^8 | 4.7×10^4 | 5.8×10^{-23} | 8.1×10^{-6} |
| 2500 | 2.67 | 1.07×10^8 | 7.3×10^4 | 8.6×10^{-23} | 1.2×10^{-5} |

The results are not very sensitive to temperature. With any reasonable value of interplanetary density ($N_s < 100 \text{ cm}^{-3}$), $N_0 \gg N_s$ in the table and the isothermal model fails. The escape proceeds adiabatically, with exospheric density varying more or less inversely as the square of the distance (Öpik and Singer 1961).

For ionized hydrogen and for $T = 2000^{\circ}$ K as a middle value (Table 3), $B = \bar{B} = 3.34$, $B_i = \frac{1}{2} B = 1.67$, $\mu_i = 1$, $s = 1.05 \times 10^6$; with $r_i/r_0 = 2$ as for an elevated iono-exospheric base (at $r \sim 1.4 \times 10^9$ cm) and for $X_i = 0.1$ equation (28a) yields a rate of

$$-\frac{1}{M} \frac{dM_i}{dt} = 5.2 \times 10^{-23} \text{ sec}^{-1}$$

without magnetic field, almost equal to that of neutral escape, but only

$$\Delta M/M = 3 \times 10^{-7}$$

when a reduction factor of 0.04 is applied, to allow for inhibition of escape by the geomagnetic field. This is small as compared to the neutral escape rate and can be neglected.

The terrestrial oceans account for 2.3×10^{-4} of the mass of the Earth; of this, 2.6×10^{-5} is hydrogen. According to Table 3, the upper limit of escape of hydrogen, at $T = 2000^\circ$, is one-third of the present store. It appears that actual escape of hydrogen, well below the upper limit, could not have depleted the terrestrial oceans to any considerable degree.

Part of the loss of hydrogen is compensated by protons of the "solar wind". Because of their high energy, they penetrate deep below the exosphere and compete with genuine terrestrial hydrogen in diffusing outwards. An influx at normal incidence of $10^9 \text{ cm}^{-2} \text{ sec}^{-1}$ (Opik, 1962b) would yield hydrogen equal to 5.0×10^{-8} of the Earth's mass during 1.4×10^{17} seconds. Over the major part of the Earth's history, the actual loss must have been impeded by the "bottleneck" of diffusion, and by the "cold trap" of the upper atmosphere, as it is now for this, presently a minor constituent (cf. Urey 1959). On the other hand, the supply of ultra-violet quanta required for breaking-up the water molecule exceeds by an order of magnitude or two the requirements of maximum escape and is not much of a limiting factor.

While hydrogen escapes, the other constituent of water, oxygen, cannot escape to any noticeable amount and is left behind. It may be that some of the free oxygen of our atmosphere is partly due to the escape of hydrogen, although it appears to be chiefly produced from CO_2 by photosynthesis of the plants. It accounts for 1.8×10^{-7} of the Earth's mass corresponding to 2.0×10^{-7}

water equivalent; at least 25 per cent of it is matched by carbon deposited photosynthetically in the Earth's crust and surface, and it is not impossible that all the free oxygen is accounted for by photosynthesis. In any case, it is a negligible amount as compared to the upper limit of loss through dissociation of water and escape. Its hydrogen equivalent is only 2.2×10^{-8} , by one order of magnitude less than even the contribution from solar wind. Considering that the solar-wind contribution must have escaped completely (otherwise hydrogen in excess of oxygen would have accumulated), a lower limit to the loss of hydrogen by escape from the Earth during 4.5×10^9 years is set by it.

According to Urey (1959), the water equivalent of oxygen required "to account for the oxidation of carbon, nitrogen, sulphur, and ferrous iron from their low value states, as they are observed in meteorites, to the oxidized states observed in the surface regions of the Earth", may be as high as 3.8×10^4 g cm⁻² (maximum estimate), corresponding to a water layer of 380 m or a hydrogen equivalent $\Delta M/M = 3.6 \times 10^{-6}$; this is 14 per cent of the present oceans, and 44 per cent of the upper limit of Table 3 ($T = 2000^\circ$). As some of the oxidation may have taken place in accreting material, during the pre-planetary or early planetary stage, the estimate is doubly an upper limit but may to a close order of magnitude approach the true value.

We have thus a lower limit to the escape of hydrogen in 4.5×10^9 years as corresponds to present solar wind, 5.0×10^{-8} of the Earth's mass; Urey (1959) finds a water equivalent loss of 20 cm or a hydrogen equivalent $\Delta M/M = 1.7 \times 10^{-8}$, 1/30 of the minimum required to dispose of injection by solar wind; the figures are close enough, suggesting that probably the present rate of escape of hydrogen from Earth is negligible.

On the other hand, the rate of dissociation of water at an early planetary stage could hardly have been much different from the maximum efficiency of present-day solar radiation. The production of free oxygen that was required for the

oxidation of the Earth's crustal materials must have been a slow process, involving time intervals of the order of 10^9 years. One way for this to work may have consisted, for example, in conditions for maximum escape (5.8×10^{-23} , Table 3) prevailing for some 6×10^{16} sec or the first 2×10^9 years of the Earth's history, after which escape of hydrogen, as well as oxidation of fresh magma were greatly slowed down. An initial period of intense plutonic activity with water vapour injected into the thermosphere by volcanic eruptions (overcoming thus the cold trap), and simultaneous exposure of abyssal magma (olivine, peridotite) which absorbed the oxygen, could well figure as a working hypothesis. It may be significant that radioactive dating has not produced terrestrial rocks older than three billion years (2.9×10^9 as an upper limit), a circumstance not in contradiction with the presumed chaotic state of the Earth's surface during its first 1.5-2 billion years.

(d) Venus.

The puzzle of the virtual absence of water and oxygen on Venus invites comments from the standpoint of escape. With possibly higher stratospheric temperatures, water vapour could have passed the cold trap, being then dissociated into atomic oxygen and hydrogen in the uppermost atmosphere (F-layer and higher, or thermosphere). The hydrogen may have escaped more easily than from Earth, and large quantities of the oxygen may have been used up in the oxidation of the crust; but an amount of oxygen comparable to that in the terrestrial oceans, if not escaping, could not have been all chemically bound at the surface without trace; it should have left a considerable amount of free oxygen in the atmosphere. This, however, is not observed. The problem is thus - could the oxygen have escaped from Venus, at least in quantities comparable to the terrestrial atmosphere, while not escaping from Earth, a planet of very similar size?

A higher temperature and the mechanism of ionic escape may provide the answer. In accordance with the concepts of thermal balance of the uppermost

terrestrial atmosphere (the "thermosphere" above 110 km on Earth) as worked out by Bates (1951), equations for the calculation of a planetary exospheric temperature have been set up for Mars by ["]Öpik (1962c, pp. 272-275); these equations can be transformed to apply to Venus. It is assumed that the unspecified source of heating of the thermosphere is inversely proportional to the square of heliocentric distance, and that the chief radiator is CO through its rotational transitions; the difference between the input from outside and the loss by radiation to space of the carbon monoxide molecule is transported downwards by conductivity which determines thus the difference of temperature between the top of the thermosphere (T_g), which is also that of the exospheric base, and its bottom (T_1). In the Venus thermosphere, at a time when water was abundant, the chief molecules must have been H, O, CO, CO₂ and N₂, of which CO₂ must have been kept down by diffusion and only CO was a strong radiator. Also, strong absorption of ultraviolet quanta by water vapour begins at 1850 Å, and has by one or two orders of magnitude a larger cross section than that for CO₂ absorption which begins efficiently at 1700 Å; H₂O when abundant is thus capable of shielding CO₂, preventing its decomposition; O₂ could also contribute to shielding (Urey 1959) but its abundance in the thermosphere must be negligible, it being completely dissociated. The abundance of CO in the Venus thermosphere therefore may have been small, despite the abundance of CO₂ on the planet, and the radiative efficiency of the thermosphere low, leading to a high exospheric temperature.

The equations for Venus can be written as follows (["]Öpik 1962c):

$$1.21 \tau + 0.50 = (1.91 + 3.85 \tau^2 f) \tau^{1/2}, \quad (44)$$

$$T_g = 2930 \tau - 850. \quad (45)$$

Here T_B is the temperature of the exospheric base, \mathcal{Z} an auxiliary variable proportional to a certain mean radiative temperature of the thermosphere, and f the relative abundance of CO in the thermosphere. $T_1 = 350^\circ\text{K}$ was assumed as the temperature at the base of the Venus thermosphere (300°K is the value for Earth); its exact value is irrelevant. The solutions, for different values of f , are contained in Table 4.

TABLE 4

Temperature (T_B) of the exospheric base for Venus as depending on the
CO-abundance (f) in the thermosphere

| | | | |
|-----------------------|------|------|------|
| f | 0 | 0.01 | 0.1 |
| \mathcal{Z} | 3.28 | 2.62 | 1.52 |
| $T_B, ^\circ\text{K}$ | 8750 | 6820 | 3600 |

The values of T_B are differentially linked to the terrestrial value, assumed to be 2050°K at $f = 0$. For Venus considerably higher temperatures result, in accordance with its smaller heliocentric distance; therefore, escape from Venus is expected to be more intense than from Earth.

In view of the great abundance of CO_2 , there must have been some CO in the Venus thermosphere, despite shielding and diffusion keeping it down. As a guess, we assume $f = 0.01$, $T = T_B = 6820$, with $\mu = 16$ as for oxygen, $s = 9.8 \text{ km/sec}$ at $r_0 = 6900 \text{ km}$ for the neutral exospheric base (800 km above ground level), $\bar{B} = B = 13.3$, $X \leq 1$; then equation (21) yields as an upper limit

$$-\frac{1}{M} \frac{dM}{dt} \leq 3.2 \times 10^{-25} \text{ sec}^{-1},$$

and for an interval of 4.5×10^9 years the total escape of neutral O becomes

$$\Delta M/M \leq 4 \times 10^{-8}$$

or an H₂O equivalent of 4.5×10^{-8} of the mass of the planet (corresponding to 47 cm of water), 6000 times less than the relative mass of terrestrial oceans or 22 per cent of terrestrial free oxygen. By cosmic standards this is negligible, although the result is very sensitive to the assumed temperature.

For ionic escape, with $T = 6820$, $X_1 \leq 1$, $\mu = 16$, $r_1/r_0 = 2$, $\bar{B} = B = 13.3$, $B_1 = 6.65$, $s = 9.8 \times 10^5$, equation (28a) yields

$$-\frac{1}{M} \frac{dM}{dt} \leq 9.8 \times 10^{-22}$$

without inhibition by a magnetic field, corresponding to a total relative loss in 4.5×10^9 years of

$$\Delta M/M \leq 3.9 \times 10^{-5}$$

a water equivalent of 4.4×10^{-5} or 19 per cent that of terrestrial oceans; on Venus it would correspond to a uniform water layer of 460 metres.

With a magnetic inhibition factor of 0.04 the relative loss becomes less than 1.8×10^{-8} , 0.8 per cent of the relative mass of terrestrial oceans or 19 metres of water layer, and ten times the amount of atmospheric oxygen on Earth.

The estimates for ionic escape are not very sensitive to temperature; yet they seem to point to a reasonably efficient process by which Venus may have lost its residual oxygen in quantities comparable to, or even exceeding

that in the terrestrial atmosphere. Most of the oxygen, however, left behind after the escape of the hydrogen must have become bound by oxidation of the crust; judging by analogy with the Earth (Urey 1959), with a similar tempo of plutonic activity, the original water store on Venus must have been much smaller than on Earth and of the order of a layer of 400 - 800 metres at most.

For ionic escape, there must be available a sufficient influx of solar ultraviolet ionizing quanta which should be greater than the number carried away by the escaping O^+ ions. According to Hinteregger (1960), the relevant flux equals 1.5×10^{11} photons per cm^2 and sec at the Earth, of a wavelength shorter than 912 \AA ; at the distance of Venus, this corresponds to an average flux over a spherical surface equal to 7×10^{10} photons $cm^{-2} \text{ sec}^{-1}$; in 4.5×10^8 years this would correspond to ionization of $2.6 \times 10^5 \text{ g/cm}^2$ of oxygen, practically equal to the water equivalent of terrestrial oceans. This sets another absolute upper limit to ionic escape, considerably exceeding the calculated limiting gas-kinetic rates which, thus, remain valid as actual upper limits.

REFERENCES

- Aller, L. H., 1953. The Atmospheres of the Sun and Stars (Ronald Press, New York).
- Bates, D. R., 1951. Proceed Physical Soc., B 64, 805.
- DeMarcus, W. C., 1958. An. J., 63, 2.
- Herzberg, G., 1952. Ap. J., 115, 337.
- Hinteregger, H. E., 1960. Ap. J., 132, 801.
- Jeans, J. H., 1925. The Dynamical Theory of Gases, 4th ed. (University Press, Cambridge).
- "Opik, E. J. and Singer, S. F., 1961. Physics of Fluids, 4, 221.
- "Opik, E. J., 1962 a. Planet. Space Sci., 1, 211.
- "Opik, E. J., 1962 b. CARUS, 1, No. 3 (in the press).
- "Opik, E. J., 1962 c. "Atmosphere and Surface Properties of Mars and Venus", in Progress in the Astronautical Sciences, ed. by Singer, S. F., Vol. 1, p. 261 (North Holland Publ. Co., Amsterdam).
- Ramsey, W. H., 1951. M. N., 111, 427.
- Spitzer, L., 1952. "The Terrestrial Atmosphere Above 300 Km" in The Atmospheres of the Earth and Planets, ed. by Kuiper, G. P., p. 211 (University Press, Chicago).
- Urey, H. C., 1959. Handbuch der Physik, 52, 363.
- Wildt, R., 1961. "Planetary Interiors" in The Solar System, ed by Kuiper, G. P. and Middlehurst, B. M., p. 159 (University Press, Chicago).